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COSMOLOGICAL IMPLICATIONS OF THE FIRST MEASUREMENT OF THE LOCAL ISM ABUNDANCE OF ^{3}HE

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ABSTRACT

Deuterium plays a crucial role in testing big-bang nucleosynthesis. Its chemical evolution, while simple (it is burned to ^{3}He), is intertwined with the more complicated evolution of ^{3}He. Gloeckler & Geiss' new measurement of the ^{3}He abundance and the HST measurement of D, both in the local ISM today, can be compared to the pre-solar nebula abundances of D and ^{3}He. Within the uncertainties, the sum of D + ^{3}He relative to hydrogen is unchanged. This provides some validation of the cosmological utility of D + ^{3}He, first suggested by Yang et al (1984), and further, indicates that over the past 4.5 Gyr there has been at most modest stellar

production of ^{3}He, in contradiction with stellar modeling, or modest stellar destruction of ^{3}He, in contradiction with some "solar spoons." While the earlier Galactic evolution of D + ^{3}He cannot be constrained directly, it is expected to be dominated by massive stars, which deplete their ^{3}He and produce metals. Based on the Galactic metallicity and the constancy of D + ^{3}He over the past 4.5 Gyr, we derive a more empirically based lower bound to the cosmological baryon density; while not dramatically different from the original bound of Yang et al (1984) based on D + ^{3}He, it alleviates some of the cosmic tension between the big-bang ^{4}He abundance and those of D and ^{3}He.

1 Introduction

Much of the current controversy concerning the consistency (Copi et al 1995a, 1995b) or inconsistency (Hata et al 1995a) of standard big-bang nucleosynthesis revolves around the chemical evolution of ^{3}He. In fact, ^{3}He is involved indirectly. Deuterium plays the crucial role in testing big-bang nucleosynthesis, as its abundance is the most sensitive to the baryon density, decreasing rapidly with increasing baryon density, and its chemical evolution brings in ^{3}He. The chemical evolution of D is straightforward: it is readily burned to ^{3}He but it is not produced in Galactic environments (Epstein, Lattimer & Schramm 1976). This means that the present deuterium abundance can be used to place an upper limit to the baryon density. This upper limit, $\eta \lesssim 9 \times 10^{-10}$ which implies $\Omega_B \lesssim 0.03h^{-2} \lesssim 0.2$, provides the linchpin in the two-decade-old argument that baryons cannot close the Universe (Reeves et al 1973). This argument is not questioned in the current controversy. (As usual, η is the present ratio of baryons to photons, Ω_B is the fraction of critical density contributed by baryons, and the Hubble constant $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with $0.4 < h < 1$.)

Using deuterium to precisely determine the baryon density, or even to set a lower limit to it, is more difficult. Because deuterium is so easily destroyed in passing through stars, the former is only possible if the deuterium abundance can be measured in a very primitive sample of the Universe. While there has been much progress toward this goal, with several detections and upper limits based on the D Ly-α feature in high redshift ($z \sim 3$), absorption-line systems (York et al 1984; Songaila et al 1994; Carswell et al 1985, 1995; Tytler & Fann 1994; Rugers and Hogan 1995; Wampler et al 1996) yielding inferred abundances in the range from 2×10^{-5} to 2×10^{-4}, there is yet no definitive result.

The derivation of a lower limit to the baryon density hinges upon the chemical evolution of ^{3}He. Since D is burned to ^{3}He and ^{3}He is far more difficult to burn, Yang et al (1984) proposed using the sum of D + ^{3}He for this purpose. Based upon stellar modeling (Iben and

Truran 1978), they assumed that at least 25% of the primordial D + ^{3}He survives stellar processing, which led to the lower limit $\eta \gtrsim 2.5 \times 10^{-10}$ and $\Omega_B \gtrsim 0.009h^{-2}$. This, together with the upper limit that follows from ^{7}Li ($\eta \lesssim 6 \times 10^{-10}$ and $\Omega_B \lesssim 0.02h^{-2}$), provides the best determination of the baryon density – between about 1% and 15% of critical density (allowing $0.4 < h < 1$; see Copi et al 1995a) – and establishes the two dark-matter problems central to cosmology: most of the baryons are dark (since $\Omega_{\rm LUM} \simeq 0.003h^{-1} < \Omega_B$) and most of the dark matter must be nonbaryonic, if as several measurements indicate $\Omega_0 \gtrsim 0.2$.

Beyond pinning down the baryon density, there is a more fundamental issue: the consistency of the standard model of primordial nucleosynthesis itself and the validity of the hot big-bang model at times as early as 0.01 sec. (By standard model of big-bang nucleosynthesis we mean: FRW cosmology, uniform distribution of baryons, three light neutrino species, and small neutrino chemical potentials.) The ^{7}Li abundance measured in almost 100 old, Pop II halo stars is consistent ("at 2σ") with the big-bang prediction provided that $\eta \simeq (1-6) \times 10^{-10}$, which overlaps the D + ^{3}He consistency interval (Copi et al 1995a). Of some concern is the primeval ^{4}He abundance: If one accepts at face value the analysis of Olive and Steigman (1995), based upon metal poor, extragalactic HII regions, then their value for ^{4}He of $Y_P = 0.232 \pm 0.003$ (stat) ± 0.005 (sys) implies $\eta \simeq (1-4) \times 10^{-10}$ (at "2σ'), which is only marginally consistent with the D + ^{3}He lower bound. It should be noted, however, that other authors (see e.g., Skillman et al 1994; Sasselov and Goldwirth 1995; and Pagel, private communication) have argued that the systematic uncertainties are at least a factor of two larger, which, owing to the logarithmic dependence of Y_P upon η would enlarge the concordance interval to $\eta \simeq (0.6-10) \times 10^{-10}$.

For some time, there has been tension between the measured abundances of ^{4}He and D + ^{3}He (see e.g., Yang et al 1984; Copi et al 1995a; Walker et al 1991; Olive et al 1995; Scully et al 1996). The resolution could involve a revision of our understanding of the evolution of ^{3}He: more stellar destruction than standard stellar models predict would lead to a lower

value of η as inferred from D + ^{3}He and lessen the tension. Alternatively, the resolution could involve an underestimation of the primeval ^{4}He abundance, by an amount $\Delta Y_P \sim 0.01$ (Copi et al 1995b); this would raise the value of η inferred from ^{4}He, making it consistent with that inferred from D + ^{3}He and conventional stellar evolution of ^{3}He. Hata et al (1995a) have argued that the discrepancy is real and is evidence for new physics, e.g., an unstable tau neutrino of mass 10 MeV or so or neutrino chemical potentials.

Eventually the deuterium abundance in high redshift Ly-α clouds will be decisive; e.g. a value $(D/H)_P \sim 10^{-4}$ implies $\eta \sim 2 \times 10^{-10}$ and would implicate the chemical evolution of ^{3}He, while $(D/H)_P \sim 3 \times 10^{-5}$ implies $\eta \sim 6 \times 10^{-10}$ and would implicate the primeval ^{4}He abundance. Until a definitive determination is forthcoming, continued scrutiny of ^{3}He – both theoretically and observationally – offers a means of addressing this important issue. Because previous measurements of the abundance of ^{3}He have raised as many questions as they have answered – variations in the abundance measured in HII regions of more than a factor of five (Bania, Rood & Wilson 1987; Wilson & Rood 1994) with some values *lower than that in the pre-solar nebula* (Black 1972; Geiss & Reeves 1972) – the measurement of the ^{3}He abundance in the local ISM by Gloeckler & Geiss (1996) is an important development. We will use it to derive a lower bound on the baryon density which is more empirically rooted and less sensitive to the questionable aspects of ^{3}He evolution.

2 The Evolution of D + ^{3}He

According to conventional stellar modeling, low-mass stars ($M \lesssim 2M_\odot$) are net producers of ^{3}He and high-mass stars preserve at least 20% or so of their ^{3}He. Integrating over a Salpeter mass function, Dearborn et al (1986) found a mean ^{3}He survival fraction of 0.8. The arguments of Yang et al (1984) and others since (see e.g., Steigman and Tosi 1992, 1995) have been predicated upon this "conventional wisdom."

As mentioned above, there are reasons to remain skeptical. Most importantly, there is precious little observational evidence to support this picture, with some recent observations apparently contradicting it, cf. Scully et al (1995). A number of authors (e.g. Gough & Weiss 1976; Schmitt, Rosner, & Bohn 1984; Zahn 1992; Hogan 1995; Wasserburg, Boothroyd, & Sackmann 1995; Charbonnel 1994, 1995; Haxton, private communication) have discussed mixing mechanisms by which ^{3}He would be brought deep enough to be burned and become depleted (to which we will refer collectively as a "solar spoon"). Wasserburg, Boothroyd, & Sackmann (1995) have emphasized how such a mixing mechanism might explain carbon and oxygen isotopic anomalies seen in certain AGB stars and in some meteoritic grains (also see, Charbonel 1994, 1995; Weiss, Wagenhuber, & Denissenkov 1996; Boothroyd & Malaney 1996) and Haxton has suggested that such a mechanism could lessen or even alleviate the solar neutrino problem.

Finally, Copi et al (1995c) have emphasized how the heterogeneity of Galactic abundances complicates attempts to infer primeval D and ^{3}He abundances. Heterogeneity arises because the Galaxy is not necessarily well mixed and material in different regions has experienced different histories of stellar-processing. Starting with the same primordial abundances, present local abundances can vary by a factor of as much as two (see Fig. 1). While the most recent HST observations (Linsky et al 1993, 1995) now show at most a 10% variation in D/H within the local ISM, earlier Copernicus and IUE observations showed a larger variation in the local ISM (for a discussion of this point see Ferlet and Lemoine 1996). And of course, the local ISM could be relatively homogeneous with the Galaxy inhomogeneous on larger scales.

The observational situation has its share of vagaries. The deuterium abundance has only been measured in nearby regions of the Galaxy, along several lines of sight in the local ISM and in the pre-solar nebula. For the pre-solar nebula, a deuterium abundance, $(D/H)_\odot = (2.7 \pm 0.5\,\mathrm{sys} \pm 1\,\mathrm{stat}\,) \times 10^{-5}$, is inferred from the difference of two measurements,

the ^{3}He abundance in the solar wind, which reflects the sum of the pre-solar D + ^{3}He (Geiss & Reeves 1972), and the ^{3}He abundance measured in gas rich meteorites (Black 1972), which reflects the pre-solar ^{3}He abundance. The higher pre-solar deuterium abundance is consistent with its expected decline with time due to stellar processing. (Measurements of the deuterium abundance using deuterated molecules, both in the solar system and throughout the Galaxy, shed little light as the effects of chemical fractionation are expected to be very significant and are difficult to disentangle.)

As mentioned above, the pre-solar abundance of ^{3}He has been measured in primitive meteorites, $(^3\mathrm{He/H})_\odot = (1.5 \pm 0.2 \pm 0.3) \times 10^{-5}$. The present ^{3}He abundance has also been measured within the Galaxy, in a number of HII regions and in a planetary nebula by means of the $^3\mathrm{He}^+$ hyperfine line (Rood, Bania, & Wilson 1992, 1995) and in a HB star by Hartoog (1979). The abundances in HII regions range from $(^3\mathrm{He/H})_{\mathrm{HII}} = 10^{-5}$ to 6×10^{-5}, suggesting a wide variation in the present abundance. On the face of it, the planetary nebula measurement, $(^3\mathrm{He/H})_{\mathrm{PN}} \sim 10^{-3}$ and the HB star measurement are consistent with the notion that low-mass stars produce significant amounts of ^{3}He. However, only a few objects have been studied and these objects represent a biased rather than representative sample – optimized to detect ^{3}He (Rood, private communication).

Heterogeneity aside, the existing Galactic ^{3}He measurements do not provide a representative sample of material. The HII regions probably preferentially sample material that has been processed through high-mass stars which destroy ^{3}He (Olive et al 1995), while the planetary nebulae and HB star represent objects with sufficiently large ^{3}He abundance to detect.

Finally, Gloeckler & Geiss (1996) have used the Solar Wind Ion Composition Spectrometer (SWICS) on the Ulysses spacecraft to determine the abundance of ^{3}He in the local ISM, yielding a value $(^3\mathrm{He/H})_{\mathrm{ISM}} = (2.1^{+0.9}_{-0.8}) \times 10^{-5}$, where the error is the sum of statistical + systematic. (They measured the abundance of slowly moving, singularly ionized

Helium atoms – so-called pick-up ions – which entered the solar system as neutral atoms, were photoionized and swept back out by the solar wind.) This measurement is important because the deuterium abundance in the ISM is also known. Together they imply $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_{\mathrm{ISM}} = (3.7 \pm 0.9) \times 10^{-5}$, which is essentially identical to the pre-solar value, $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_{\odot} \simeq (4.2 \pm 0.7 \pm 1) \times 10^{-5}$. The constancy of the D + ^{3}He abundance over the past 4.5 Gyr is striking and provides general confirmation of the cosmological utility of D + ^{3}He as proposed by Yang et al (1984), though one must be mindful of the details of its implementation.

3 Discussion

Gloeckler & Geiss' measurement is noteworthy because it allows the evolution of D + ^{3}He to be addressed empirically for the first time. The message is simple: over the past 4.5 Gyr it has not changed dramatically. This means that those stars that have contributed significantly to the local ISM over this period are not significant producers or destroyers of ^{3}He. This is not a trivial fact, as the increase in ^{3}He and the decline in D over this time (almost a factor of two) indicate substantial stellar processing.

According to chemical-evolution models, low-mass stars ($\sim 1M_{\odot} - 1.5M_{\odot}$) have made the dominant contribution to the ISM over the past 4.5 Gyr (Truran & Cameron 1971; Rood, Steigman & Tinsley 1976; see also the recent discussion by Scully et al 1995). Such a constancy of D + ^{3}He implies that low-mass stars cannot be significant producers of ^{3}He, which is at variance with the predictions of standard stellar models. Likewise, there is no evidence to support significant destruction of ^{3}He by low-mass stars as predicted with an efficient solar spoon at work (see e.g., Hogan 1995). However, Dearborn (private conversation) has shown that the slow mixing models that fit the oxygen and carbon isotopic anomalies do not completely deplete ^{3}He; they reduce the amount of ^{3}He that would have been returned to

the ISM by at most 80%. If this is indeed the case, a solar spoon could be consistent with the ISM value of D + ^{3}He.

Gloeckler & Geiss' result does little to directly constrain the earlier evolution of D + ^{3}He. The stellar mass function at earlier times is expected to favor more massive stars, which deplete ^{3}He. Since the Gloeckler & Geiss result constrains low-mass star destruction of ^{3}He, massive stars are the only possible way to greatly deplete ^{3}He. Massive stars produce heavy elements, and thus there is a limit to the amount of material that could have been processed through massive stars.

In particular, the ejecta of Type II supernovae are about 10% oxygen by mass, which implies that only a small fraction of the material in the local ISM – roughly 10% – could have been processed through massive stars. Taken together with the apparent constancy of D + ^{3}He over the last 4.5 Gyr, this suggests that the primordial value of D + ^{3}He cannot differ greatly (about a factor of two for simple closed galaxy models) from the present value. This leads to the lower bound, $[(\mathrm{D}+^3\mathrm{He})/\mathrm{H}]_P \lesssim 10^{-4}$ which is almost identical to that used by Yang et al (1984), but now with firmer empirical roots.

An important assumption underlies the above argument, that all the metals ejected by massive stars make their way back into the ISM. It is possible that metals produced in the early supernova-active phase of the proto-Galaxy (or the proto-galactessimals that merged to form the Galaxy) were ejected into the surrounding IGM. There is some evidence for this; observations of the x-ray emitting gas in rich clusters show metallicities that are slightly less than solar, distributed in a gas mass that is roughly ten times that in galaxies. If the Galaxy ejected a comparable amount of metals ten times more material could have been processed through massive stars, depleting ^{3}He dramatically. (Note, material depleted in ^{3}He is still returned to the ISM in a pre-supernova stellar wind.) However, as Copi et al (1995c) showed, even a relaxed metallicity constraint does not allow the primordial value of $(\mathrm{D}+^3\mathrm{He})/\mathrm{H}$ to exceed about 2×10^{-4}.

Finally, let us use the information gleaned from this first measurement of the ^{3}He abundance in the ISM to make more quantitative statements about the value of the baryon density and the consistency of standard big-bang nucleosynthesis. The stochastic history approach of Copi et al (1995c) allows one to use the pre-solar values of ^{3}He and D + ^{3}He to infer both their primordial values and η, while allowing for the heterogeneity of Galactic abundances. The physical input needed is the mean properties of stellar processing. Based upon Gloeckler & Geiss' measurement, we consider two possibilities for the evolution of ^{3}He in low-mass stars, (1) low-mass stars preserve their ^{3}He, but do not produce ^{3}He; and (2) low-mass stars destroy 80% of the ^{3}He they would have returned to the ISM, and two possibilities for metal ejection by massive stars, (a) massive stars return most of the metals they make to the ISM and (b) massive stars only return 10% of the metals they make to the ISM (the rest ejected into the IGM). For these four possibilities, 1a, 1b, 2a, and 2b, we have constructed Monte-Carlo likelihood functions for the baryon-to-photon ratio η, which are shown in Figure 2. The 95% credible intervals are: $\eta_{1a} = (5-7)\times 10^{-10}$; $\eta_{2a} = (3-6)\times 10^{-10}$; $\eta_{1b} = (2-5)\times 10^{-10}$; and $\eta_{2b} = (2-5)\times 10^{-10}$. For reference, the very naive assumption that D + ^{3}He has remained unchanged since primordial nucleosynthesis implies $\eta \sim 5\times 10^{-10}$ and a primeval D abundance $(\mathrm{D/H})_P \sim 4\times 10^{-5}$.

Regarding the consistency of big-bang nucleosynthesis, Model 1a continues to implicate ^{4}He as the culprit (or the standard model of big-bang nucleosynthesis itself). Models 1b, 2a, and 2b lessen the tension between ^{4}He and ^{3}He and D, with Models 1b and 2b essentially eliminating the tension all together. The full range for the baryon density based upon these models, $\eta \simeq (2-7)\times 10^{-10}$, is essentially the same as that found previously by Copi et al (1995a). We note that the models that lessen the tension, lead to a stronger upper limit to η and strengthen the case for nonbaryonic dark matter. For example, for Models 1b and 2b, the joint 95% credible region for all the light-elements corresponds to $\Omega_B = (0.007-0.018)h^{-2}$.

In sum, the measurement of the interstellar ^{3}He abundance by Gloeckler & Geiss (1996)

allows the chemical evolution of D + ^{3}He to be addressed empirically for the first time, and in turn, tests primordial nucleosynthesis and its prediction for the baryon density. Their measurement indicates little evolution of D + ^{3}He over the past 4.5 Gyr, generally confirming the the argument of Yang et al (1984), suggesting that low-mass stars are not significant producers or destroyers of ^{3}He, and calling into question standard stellar models as well as efficient solar spoons. Little can be learned directly from their result about the earlier evolution of D + ^{3}He, which is likely to be dominated by high-mass stars. However, the fact that high-mass stars also produce metals limits the amount of ^{3}He depletion, even if 90% of the metals they produce are ejected from the Galaxy. We have used this fact together with Gloeckler & Geiss' result to establish a more empirically based lower bound to the baryon-to-photon ratio, $\eta \gtrsim 2 \times 10^{-10}$. While only slightly less stringent than the bounds of Yang et al (1984) and Copi et al (1995a), it suggests the apparent tension between the big-bang abundance of ^{4}He and those of D and ^{3}He involves the chemical evolution of ^{3}He.

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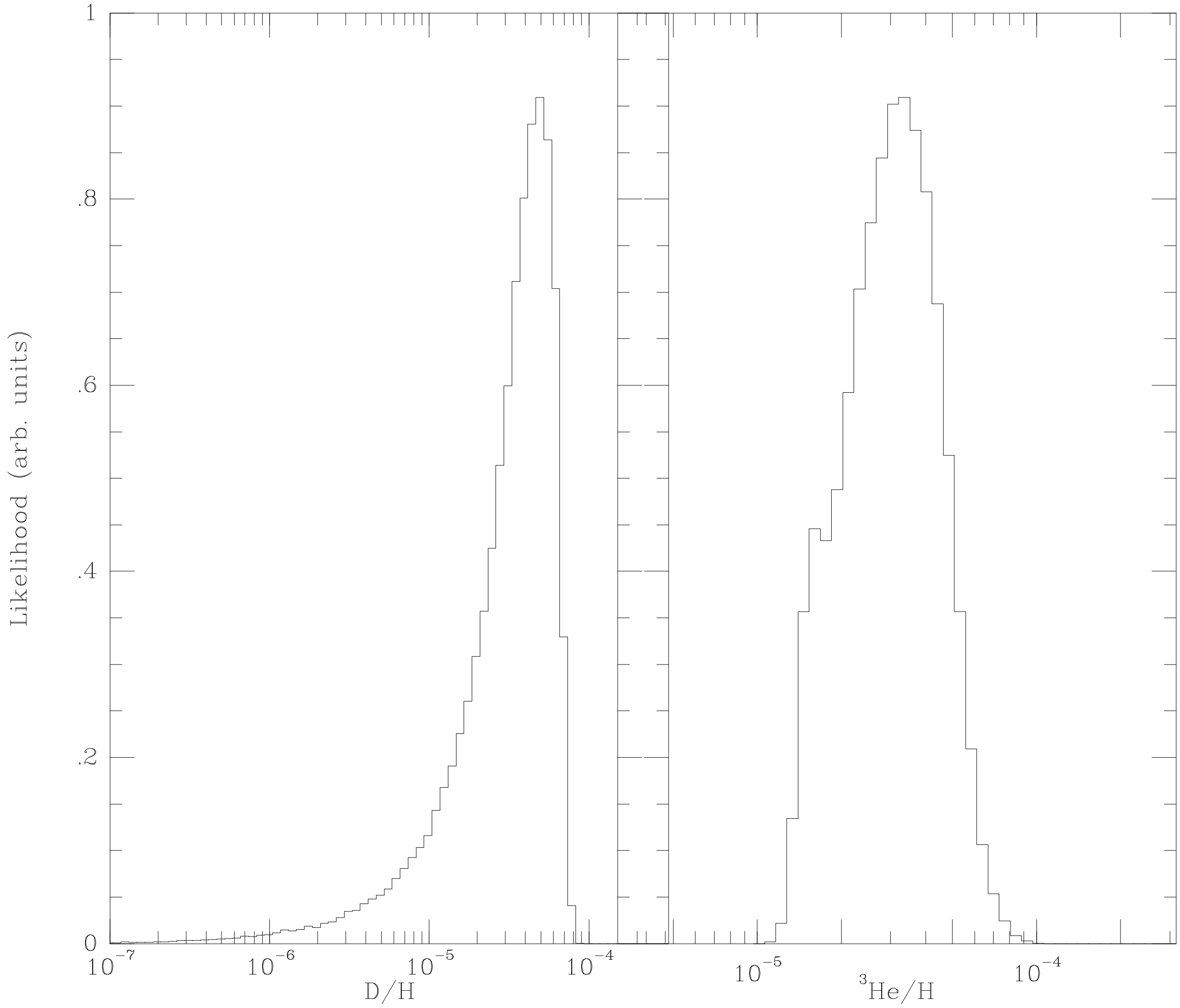

Figure 1: The variation in present D and ^{3}He abundances expected today due to differing histories. Here we have assumed $\eta = 3.2 \times 10^{-10}$ to fix the primordial values.

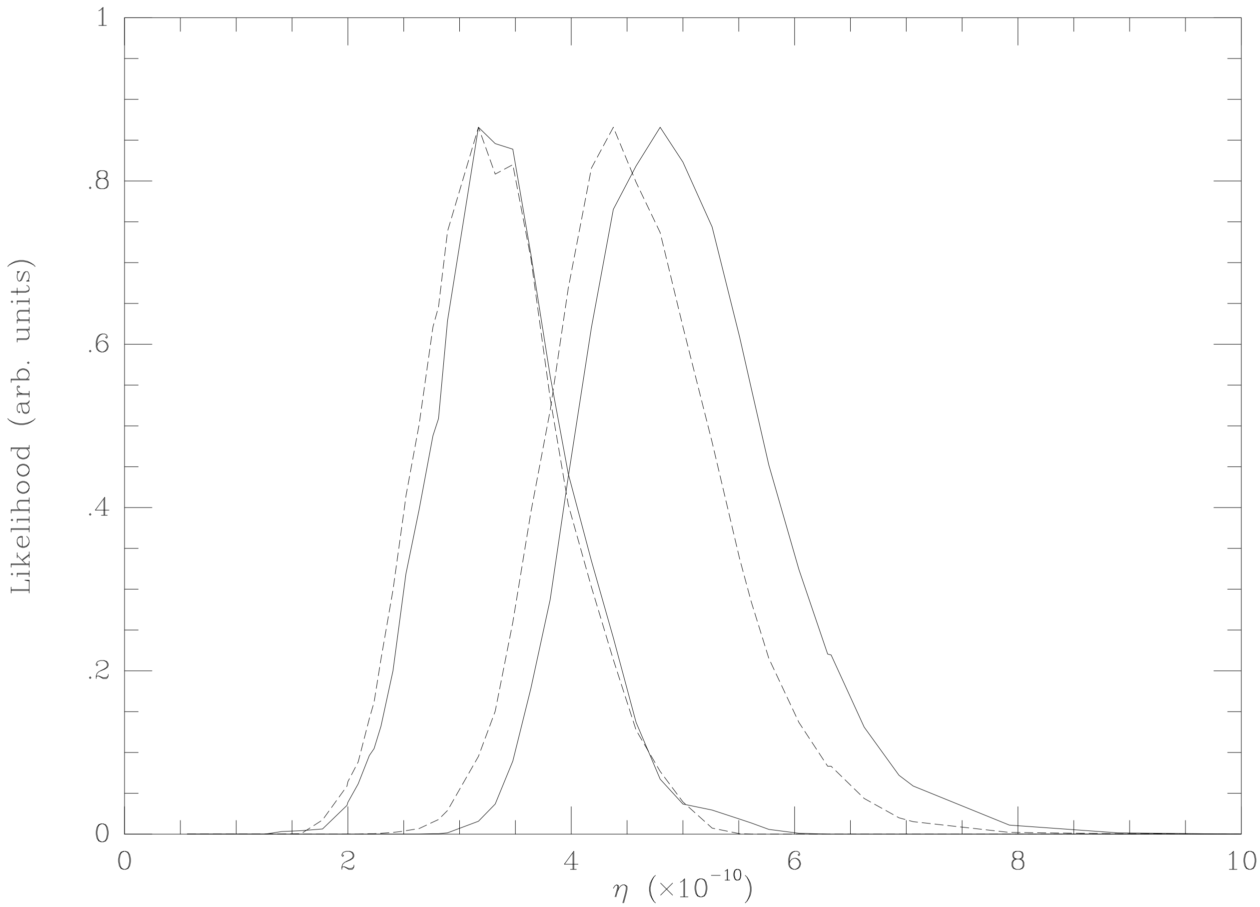

Figure 2: Monte-Carlo likelihood functions for the baryon-to-photon ratio based upon D and ^{3}He for Models 1a (right solid curve), 2a (right broken curve), 1b (left solid curve), and 2b (left broken curve).